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Effects of an Uncomposted Municipal Waste Processing By-Product on Prairie Grass Establishment

Ryan R. Busby,* Dick L. Gebhart, and H. Allen Torbert

ABSTRACT

A garbage processing technology has been developed that sterilizes and separates inorganic and organic components of municipal solid waste. A study was initiated to evaluate the uncomposted organic by-product of this process as a soil amendment for establishing native prairie grasses on disturbed Army training lands. The waste was incorporated into sandy soils at Fort Benning Military Reservation on two sites: a moderately degraded and a highly degraded soil. The waste material was applied at rates of 0, 17.9, 35.8, 71.6, and 143 Mg ha^{-1} and seeded with native prairie grasses to assess its effects on vegetation for two growing seasons, with an additional unseeded control treatment for comparison to natural recovery. The addition of uncomposted waste increased percent composition and basal cover of switchgrass (*Panicum virgatum* L.) at both sites and percent composition of big bluestem (*Andropogon gerardii* Vitman) at one site. Indiangrass [*Sorghastrum nutans* (L.) Nash] was negatively affected by the addition of the waste material at both sites. Biomass in the 143 Mg ha^{-1} treatment increased 4180% compared to the seeded control at the highly degraded site. Plant uptake of P and Na increased at both sites and an apparent Fe toxicity problem was alleviated at the highly disturbed site with increasing application rates. Because perennial grass establishment improved so dramatically with increasing application rates, land application of this uncomposted waste material could be considered a viable and beneficial alternative to current waste management practices for degraded Army lands.

In 2003, the USA produced 214 Tg of municipal solid waste (MSW) (USEPA, 2005). The U.S. Army alone generated more than 1.2 Tg of MSW in fiscal year 2003 (USDOD, 2003). Because most Army landfills are near capacity and construction of new landfills is unfavorable, much installation MSW is sent to local municipal landfills, which results in higher costs to ship it off post. Reuse of this waste could result in significant cost saving. However, composting of the organic materials has not been widely established, mainly due to high required cost of facilities and the inefficiencies of producing safe, usable material.

A solid waste processing technology has been developed that separates the organic fraction of garbage from the recyclable materials and sterilizes it, producing a pulp-like material called Fluff (Bouldin and Lawson, 2000). This technology is currently in use in Warren County, TN, where a 95% recycling rate has been achieved for the county's municipal waste, with the bulk of the organic by-product composted for use as topsoil replacement in the horticultural industry (Croxton et al., 2004). However, because the material is sterilized and contains few contaminants, its utilization as a soil amendment does not require composting and the concomitant management costs (unpublished data, 2003). Unfortunately, undecomposed organic matter is often attributed to phytotoxic effects and nutrient immobilization when applied to soil (Bengston and Cornette, 1973; Terman et al., 1973; Zucconi et al., 1981; Chanyasak et al., 1983a, 1983b; Wong, 1985).

Carbon and N mineralization of Fluff appears to be dependant on the nutrient status of the soil and, in infertile soils, C retention and N immobilization occur for an extended period of time (Busby et al., 2006). One potential use for this material is for establishing native vegetation that is adapted to nutrient limited soils and, therefore, benefits greatly from a reduction in weed competition under N-limiting conditions (McLendon and Redente, 1992; Wilson and Gerry, 1995; Paschke et al., 2000). Perennial warm-season grasses, such as those native to the tallgrass prairie of North America, are well adapted to harsh environmental conditions, giving them a competitive advantage in poor soils (Jung et al., 1998; Wilson and Gerry, 1995; Skeel and Gibson, 1996; Levy et al., 1999). These grasses are used abundantly in reclamation, as they develop extensive root systems that penetrate deep into soils, providing a very effective safeguard against erosion (Drake, 1983). Although these species are highly suited to conservation plantings, establishment is a significant barrier to successful utilization, as weedy species can easily overtake them and cause failure, especially in N-rich soils (Launchbaugh, 1962; Warnes and Newell, 1998; Brejda, 2000). Preliminary research using big bluestem, indiangrass, switchgrass, and Virginia wildrye (*Elymus virginicus* L.) indicated no negative effects on germination in Fluff-amended soil (Busby, 2003). Initial field data suggests that establishment and P acquisition of warm-season grasses was improved in a silt loam soil receiving up to 35.8 Mg ha^{-1} of Fluff without any detrimental environmental consequences (unpublished data, 2003).

The Army owns almost 5 million hectares of land in the USA, including 73 installations with greater than 4000 hectares each, that routinely require rehabilitation and maintenance to support training activities (USDOD, 2001). These lands are often highly eroded and incur significant

R.R. Busby and D.L. Gebhart, U.S. Army Engineer Research and Development Center, Construction Engineering Research Lab., P.O. Box 9005, Champaign, IL 61826; and H.A. Torbert, USDA–ARS, National Soil Dynamics Lab., 411 S. Donahue Dr., Auburn, AL 36832. Names are necessary to report factually on available data: however, neither the U.S. Department of the Army nor the USDA guarantees or warrants the standard of the production; the use of the name by the Army or the USDA implies no approval of the product to the exclusion of others that may be suitable. Received 3 Jan. 2006. *Corresponding author (ryan.r.busby@erdc.usace.army.mil).

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Abbreviations: MSW, municipal solid waste; PLS, pure live seed.

losses of topsoil, organic matter, and nutrients, and are prone to invasion by exotic plant species, leading to further ecological degradation. Consequently, the Army is required by law to control water and air pollution, maintain ecosystem sustainability, protect native biological diversity, and control the spread of exotic species on its training lands. Thus, the Army could derive significant benefits from utilization of its own MSW to aid in management of its training lands. This study examined whether an undecomposed waste material could be used as a soil amendment to improve establishment of native grasses on degraded Army training lands.

MATERIALS AND METHODS

Study Site

The field study was performed in West-Central Georgia at Fort Benning Military Reservation. Two sites were selected based on their high degree of dissimilarity. The first site was located on a productive upland soil used previously for dove food plots, where millet was grown to attract doves for hunters. The second site was located at the bottom of a borrow pit approximately 20 hectares in area and 4 to 5 m deep where the Argillic and Kandic layers have been mined. The Dove Field soil is a Troup loamy fine sand (loamy, kaolinitic, thermic Grossarenic Kandiudults) and the Borrow Pit soil is an Orangeburg loamy sand (fine-loamy, kaolinitic, thermic Typic Kandiudults) (USDA–NRCS, 2004).

Climate data from the Columbus Metropolitan Airport, Columbus, GA, is located approximately 15 km north of the study sites and was analyzed for the duration of the experiment. Precipitation for the 30 yr before the study averaged 123 cm, with the highest precipitation occurring in March and July. During 2003, the first year of the study, total precipitation was 143 cm due to a wetter-than-average summer (USDOC–NOAA, 2004). During 2004, total precipitation was 124 cm (USDOC–NOAA, 2005).

Experimental Design

Before any experimentation, the Fluff was extensively analyzed for numerous regulated compounds (unpublished data, 2003). Of the regulated contaminants, only heavy metals were found to be of concern, but all were at least an order of magnitude less than EPA ceiling limits for biosolids application (40 CFR 503, 1999). Based on established limits, lead was found to be the contaminant of primary concern, but only at Fluff rates far beyond what would logically be used for soil amelioration. In previous research with application rates up to 35.8 Mg ha^{-1}, the application of Fluff led to a minimal increase in soil concentrations of lead (unpublished data, 2003). Agriculturally significant Fluff properties are presented in Table 1. Plots were established at each site in February 2003 and application rates of 0, 17.9, 35.8, 71.6, and 143 Mg of Fluff per ha dry weight were incorporated into the top 15 cm of soil. Waste material was weighed and hand spread on the plots, disked twice to thoroughly mix it into the soil, and seeded with 'Earl' big bluestem, 'Cheyenne' indiangrass, 'Alamo' switchgrass, and Virginia wildrye using a drill seeder. Seed was obtained from Turner Seed Company (Breckenridge, TX) and planted in a mixture to yield 54 kg pure live seed (PLS) ha^{-1}, containing 13.5 kg PLS ha^{-1} of each species. Unseeded and seeded controls were used to compare differences between natural recovery and seeding following disturbance. Plots measured 3.7 by 4.9 m with 0.6 m buffers between plots in each block and 2.4 m buffers between blocks. Each study site was a randomized complete block with four replications, blocked by slope. First year data collection occurred in October 2003. Second year data was collected in October 2004. Data collection consisted of basal vegetative cover, plant species composition, aboveground biomass, and plant chemical analysis. Additional soil analysis was conducted to measure pH, bulk density, total C and N, and extractable B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, P, Pb, and Zn (Torbert et al., unpublished data, 2006).

Table 1. Agriculturally significant Fluff properties.

pH	6.5	Fe, mg kg^{-1}	2460
C/N	32	Mn, mg kg^{-1}	130
C, %	39.8	Zn, mg kg^{-1}	234
N, %	1.26	B, mg kg^{-1}	35
P, mg kg^{-1}	1900	Cu, mg kg^{-1}	47.7
K, mg kg^{-1}	2170	Co, mg kg^{-1}	2
Ca, mg kg^{-1}	13600	Na, mg kg^{-1}	5169
Mg, mg kg^{-1}	1400	Pb, mg kg^{-1}	65.4

Vegetation Sampling

Species composition and basal vegetative cover were measured using a 10-point frame (Sharrow and Tober, 1979), with 200 random points taken per plot. Plant species composition was measured as relative percent composition of each species to the total vegetation encountered (percentage of total vegetation). Basal cover was measured as absolute basal cover of each species and absolute basal cover of total vegetation (percentage of total ground covered).

Plant biomass was collected by clipping five random samples per plot to a height of 1 cm using 30 by 60 cm quadrats. Biomass samples consisting of composite samples of all species present were dried at 60°C until weight loss was complete and reweighed (Bonham, 1989). Composite biomass samples were analyzed by the USDA–ARS National Soil Dynamics Lab. Analysis was performed for total Ba, Ca, Fe, K, Mg, Mn, Na, P, and S with procedures outlined by Hue and Evans (1986) using inductively coupled plasma spectrophotometry (Spectro CirOS, FCSMi, Spectro Analytical Instruments, Fitchburg, MA) and total N using a LECO CN 2000 Analyzer (LECO Corp., Saint Joseph, MI) (Bremner, 1996; Soltanpour et al., 1996).

Statistical Analysis

Site, year, and Fluff treatment effects on composition, cover, biomass, and plant chemical concentration were tested with repeated measures analysis of variance using the PROC MIXED procedure in SAS (Littel et al., 1996; SAS Institute, 2001). Site effects were so extreme ($P < 0.0001$) for all variables that site effects were removed from further analysis to focus on treatment effects. Means were obtained using least squares means for significant effects and were separated using linear contrast statements at the 0.05 probability level.

RESULTS AND DISCUSSION

Species Composition

A total of 21 species were sampled in the research plots over 2 yr. At the Dove Field and Borrow Pit sites, 17 species and 9 species were encountered, respectively. The three seeded warm-season grasses were dominant across sites and years. Virginia wildrye established poorly and was only encountered a few times at the Dove

Field site. Bermudagrass [*Cynodon dactylon* (L.) Pers.] and Mexican clover (*Richardia scabra* L.) dominated the unseeded control plots at the Dove Field site and were the most common unplanted species encountered across that site. The Borrow Pit had very little unplanted vegetation present and unseeded control plots were devoid of any vegetation. In the unseeded control plots of the Dove Field site, bermudagrass comprised 53.1% and Mexican clover comprised 32.0% of the total vegetation composition, with bermudagrass unaffected by and Mexican clover increasing significantly over time. For analysis of planted species, unseeded control plots were therefore removed from the composition data.

Switchgrass was the dominant species, as it comprised 64.3 and 44.4% of the total vegetation at the Borrow Pit and Dove Field sites, respectively (Table 2). Switchgrass relative composition increased significantly over time in the Dove Field but remained unchanged in the Borrow Pit. Similarly, application rate had no effect on switchgrass relative composition in the Borrow Pit, but in the Dove Field in 2004, switchgrass relative composition was directly related to application rate, with a mean percent composition of 36.6% in the seeded control compared to 64.7% in the 143 Mg ha^{-1} treatment (Table 2). Big bluestem relative composition comprised 19.7% of the total vegetation at the Dove Field site and 18.9% at the Borrow Pit, was unaffected by application rate, and increased over time at both sites (Table 2).

Indiangrass relative composition comprised 23.1% of the Dove Field and only 8.2% of the Borrow Pit total vegetation composition. Further, indiangrass relative composition decreased over time at both sites and was relatively unaffected by application rate in the Borrow Pit. At the Dove Field site, however, indiangrass relative composition was inversely related to application rate in 2004, comprising 26.4% of the total composition in the seeded control but only 9.8% in the 143 Mg ha^{-1} treatment (Table 2). Combined, planted grass species comprised 98.2% of the total species composition of the Borrow Pit and 87.3% of the Dove Field plots. Application rate had no effect on percent composition of total planted grasses at either site (Table 2). Planted grass relative composition was unchanged from 2003 to 2004 at the Borrow Pit site but increased at the Dove Field site, primarily due to an increase in switchgrass.

Cover

Total basal vegetative cover across treatments averaged 12.8% at the Dove Field site and 6.4% at the Borrow Pit site (including unseeded controls). Over time, Dove Field total cover remained unchanged while cover increased significantly in the Borrow Pit. Total basal vegetative cover also increased significantly with increasing application rate at both sites, with a much greater effect in the Borrow Pit than in the Dove Field, especially in 2004 (Table 3). Bermudagrass and Mexican clover, the two dominant species in the unseeded control plots at the Dove Field site, had mean basal cover values of 3.9 and 2.4%, respectively. At the Borrow Pit, unseeded control plots were virtually bare. Seeded plots were analyzed only for basal cover of planted grass species, as no other species occurred in measurable amounts to conduct a statistical analysis and these species were not found in any unseeded control plots.

Switchgrass had the highest percent basal cover of the planted grass species, with mean basal cover of 4.9% in the Borrow Pit and 6.3% in the Dove Field, and increased between 2003 and 2004 at both sites. Application rate had a significant effect on switchgrass basal cover at both sites, with a much greater effect at the Borrow Pit, as mean basal cover ranged from 1.6% in the seeded control to 9.5% in the 143 Mg ha^{-1} treatment in 2004 (Table 4). Mean basal cover of big bluestem was 2.8% at the Dove Field and 1.7% at the Borrow Pit and increased over time at both sites. Application rate had no effect on big bluestem basal cover in the Dove Field but had a significant effect in the Borrow Pit, with an increase from 0.3% in the seeded control to 4.6% in the 143 Mg ha^{-1} treatment in 2004 (Table 4).

Indiangrass mean basal cover was 3.0% in the Dove Field and 0.7% in the Borrow Pit. Basal cover of indiangrass did not change over time in the Borrow Pit

Table 2. Relative composition of planted grass species at increasing Fluff application rates over two growing seasons in the Dove Field and Borrow Pit sites. Values represent means of 200 point samples replicated four times.

	Switchgrass		Big bluestem		Indiangrass		Total planted grass†	
Fluff rate	2003	2004	2003	2004	2003	2004	2003	2004
Mg ha^{-1}	%							
				Dove Field				
0	32.1 a‡	36.6 c	13.2 a	28.6 a	35.5 a	26.4 a	80.7 a	91.7 a
17.9	39.2 a	50.2 abc	17.2 a	29.8 a	26.1 a	16.4 ab	82.5 a	96.4 a
35.8	30.8 a	38.6 bc	16.8 a	33.3 a	32.2 a	24.7 a	79.8 a	96.6 a
71.6	44.7 a	58.9 ab	15.3 a	17.5 a	24.5 a	13.3 ab	84.4 a	89.7 a
143	48.6 a	64.7 a	11.7 a	14.1 a	21.6 a	9.8 b	82.5 a	88.6 a
				Borrow Pit				
0	42.9 a	79.2 a	10.7 a	16.7 a	0.0 b	0.0 a	100.0 a	100.0 a
17.9	69.4 a	66.3 a	14.6 a	15.2 a	8.8 ab	6.7 a	96.4 a	94.4 a
35.8	62.1 a	62.1 a	12.7 a	29.7 a	20.3 a	8.1 a	98.3 a	100.0 a
71.6	68.4 a	61.9 a	17.1 a	25.6 a	14.5 a	8.3 a	100.0 a	97.2 a
143	67.4 a	62.9 a	17.9 a	29.2 a	10.9 ab	4.3 a	98.5 a	97.0 a

† Grasses were planted at 13.5 kg PLS ha^{-1} per species.
‡ Means in each column for each site with the same letter are not significantly different at the 0.05 probability level.

Table 3. Total basal vegetative cover at increasing Fluff application rates over two growing seasons in the Dove Field and Borrow Pit sites. Values represent means of 200 point samples replicated four times.

Fluff rate	2003	2004
Mg ha^{-1}	%	
	Dove Field	
Unseeded control	6.8 c†	8.3 c
0	11.3 b	13.0 b
17.9	12.6 ab	14.3 ab
35.8	12.6 ab	13.9 ab
71.6	13.6 ab	16.1 a
143	16.9 a	14.9 ab
	Borrow Pit	
Unseeded control	0.0 d	0.1 d
0	3.3 c	2.0 cd
17.9	3.8 c	5.6 bc
35.8	5.9 b	7.8 b
71.6	9.5 a	12.4 a
143	10.9 a	15.4 a

† Means in each column for each site with the same letter are not significantly different at the 0.05 probability level.

but decreased in the Dove Field from 2003 to 2004. Further, application rate had no effect on indiangrass basal cover at the Dove Field site in 2003, but in 2004 had an inverse effect, as indiangrass cover decreased from 3.3% in the seeded control to 1.4% in the 143 Mg ha^{-1} treatment (Table 4). At the Borrow Pit, indiangrass basal cover increased slightly with increasing application rate. However, due to indiangrass comprising only a minor component of the vegetation, the statistical differences observed in indiangrass cover lack any ecological significance (Table 4). Total planted grass basal cover had a mean of 12.2% in the Dove Field compared to 7.5% in the Borrow Pit and increased over time at both sites. Application rate had a significant effect on planted grass cover in the Borrow Pit, with mean cover values of 14.9% in the 143 Mg ha^{-1} treatments compared to 2.0% in the seeded control (Table 4). However, planted grass basal cover was relatively unaffected by application rate at the Dove Field site.

Because the planted grass species constituted almost all vegetation that was sampled in the seeded plots (98% in the Borrow Pit and 87% in the Dove Field) and resulted in mean basal cover values of 7.5 and 12.2%, respectively, establishment of a native grass community was considered successful at both sites. Switchgrass appeared to be the best suited species as it dominated all seeded sites and comprised the highest relative percentage composition and basal cover of all species present. It also responded the most favorably to Fluff application as basal cover increased significantly with increasing application rate at both sites, and it became an even larger component of total vegetation with increasing application rate in the more fertile site. Additionally, switchgrass performed so well that the majority of plants produced seed during the first growing season at both sites (Busby, personal observation 2003), which may have contributed to increased dominance the following year. Big bluestem appeared to be unaffected by application rate at the Dove Field site, but basal cover increased significantly with increasing application rate at the Borrow Pit. Given that the Dove Field site was much more conducive to establishment than the Borrow Pit, this may have been the result of oversupplying nutrients with the high rates that big bluestem was not able to exploit at the Dove Field, while overcoming deficiencies and creating more favorable growing conditions at the Borrow Pit positively influenced big bluestem growth.

Indiangrass initially performed well in the Dove Field, but remained only a minor vegetation component at the Borrow Pit. Given that indiangrass diminished over time and in response to increased Fluff, while the other two dominant species increased, it appears that indiangrass was not able to effectively compete with switchgrass and big bluestem at either site in the presence of Fluff-amended soil. Indiangrass high relative composition in the controls indicates that it was competitive in unamended soils. However, its low relative composition in the higher application rates indicates that it was not able to effectively exploit any benefits provided by the amended soils in the manner observed by switchgrass. Further, because it was so much more prevalent in the Dove Field than in the Borrow Pit, this indicates that indiangrass was not as tolerant to the highly unfavorable growing conditions in the Borrow Pit as were the other species.

Table 4. Basal cover of planted grass species at increasing Fluff application rates over two growing seasons in the Dove Field and Borrow Pit sites. Values represent means of 200 point samples replicated four times.

	Switchgrass		Big bluestem		Indiangrass		Total planted grass	
Fluff rate	2003	2004	2003	2004	2003	2004	2003	2004
Mg ha^{-1}	%							
				Dove Field				
0	3.8 b†	4.8 b	1.8 a	3.8 a	3.6 a	3.3 a	9.1 a	11.8 b
17.9	5.0 ab	7.1 ab	2.3 a	4.3 a	3.3 a	2.4 ab	10.5 a	13.8 ab
35.8	4.2 b	5.4 b	2.1 a	4.6 a	4.3 a	3.4 a	10.6 a	13.4 ab
71.6	6.1 ab	9.5 a	2.1 a	2.9 a	3.3 a	2.1 ab	11.5 a	14.5 a
143	8.0 a	9.4 a	2.0 a	2.0 a	3.5 a	1.4 b	13.6 a	12.8 ab
				Borrow Pit				
0	1.5 c	1.6 d	0.4 b	0.3 c	0.0 c	0.0 b	3.3 c	2.0 c
17.9	2.6 bc	3.9 cd	0.5 b	0.9 bc	0.4 bc	0.4 ab	3.6 c	5.4 bc
35.8	3.6 b	5.0 bc	0.8 b	2.3 abc	1.1 ab	0.5 ab	5.8 b	7.8 b
71.6	6.5 a	7.3 ab	1.6 a	3.4 ab	1.4 a	1.1 a	9.5 a	12.0 a
143	7.4 a	9.5 a	2.0 a	4.6 a	1.1 ab	0.6 ab	10.8 a	14.9 a

† Means in each column for each site with the same letter are not significantly different at the 0.05 probability level.

Table 5. Aboveground biomass at increasing Fluff application rates over two growing seasons in the Dove Field and Borrow Pit sites. Values represent means of five subsamples replicated four times.

Fluff rate	Dove Field		Borrow Pit	
$Mg\ ha^{-1}$	$g\ m^{-2}$			
	2003	2004	2003	2004
Unseeded control	242.7 d†	290.9 c	0.0 d	0.0 d
0	269.2 d	391.8 c	17.6 d	13.9 d
17.9	343.7 c	616.5 b	45.7 cd	90.3 cd
35.8	427.8 bc	612.7 b	73.2 c	122.2 c
71.6	467.8 ab	749.0 b	202.1 b	402.6 b
143	539.1 a	1059.2 a	344.6 a	581.6 a

† Means in each column for each site with the same letter are not significantly different at the 0.05 probability level.

Biomass

Harvestable aboveground biomass was not produced in the unseeded control plots at the Borrow Pit site due to an almost complete lack of vegetation, but the zero values were kept in the analysis for comparison. Aboveground biomass increased significantly over time at both sites. Biomass was much higher in the Dove Field than in the Borrow Pit across application rates, but both sites responded very well to increased Fluff application (Table 5). In the Dove Field, biomass remained relatively constant in the unseeded control at <300 g m^{-2} but almost doubled in the 143 Mg ha^{-1} treatment from 539 to 1059 g m^{-2} from 2003 to 2004. In the Borrow Pit, the unseeded control lacked any biomass throughout the study but the 143 Mg ha^{-1} treatment increased from 345 to 582 g m^{-2} over time.

Chemical Composition

Only plant material harvested from the seeded treatments were analyzed for chemical composition due to: (i) lack of harvestable biomass in the unseeded control plots at the Borrow Pit and (ii) a dissimilar vegetation community in the unseeded control plots at the Dove Field compared to all seeded treatments, which would not provide a suitable comparison due to differing nutrient requirements. All seeded treatments were analyzed together. Corresponding soil analysis is presented by Torbert et al. (unpublished data, 2006) and illustrates the highly dissimilar chemical properties of the two soils. Briefly, soil pH from 0 to 5 cm in the control plots were 6.4 and 5.3 at the Dove Field and Borrow Pit sites, respectively. The Dove Field site contained 13.0 g kg^{-1} C, 0.6 g kg^{-1} N, 29.7 mg kg^{-1} extractable P, and 53.5 mg kg^{-1} extractable K in the top 0 to 5 cm of soil. The Borrow Pit site contained 2.2 g kg^{-1} C, 0.1 g kg^{-1} N, 2.02 mg kg^{-1} extractable P, and 9.1 mg kg^{-1} extractable K in the top 0 to 5 cm of soil.

Macronutrients

For the seeded treatments, plant N concentrations ranged from 0.239 to 0.859% and decreased over time at both sites. These concentrations fall within the normal range for range grasses given by Munshower (1994). In the Dove Field, vegetation in the 143 Mg ha^{-1} treatment had significantly higher N than all other treatments in 2003, but treatment effects were not apparent in 2004. In the Borrow Pit, the seeded control vegetation exhibited the highest N concentration in both years with a significantly higher concentration than all other treatments in 2004 (Table 6). The increase in N in the Dove Field is likely attributable to increased application rate. However, the inverse relationship seen at the Borrow Pit may be due to other factors, including stress responses to problems occurring in the soil, given the extremely low biomass production in the controls.

Plant P concentrations ranged from 120.00 to 2307.35 mg kg^{-1} and decreased over time at both sites. The normal plant P concentration for grasses is in the range of 1000 to 3000 mg kg^{-1} (Munshower, 1994) and all but three samples were below this range in the Borrow Pit. Of these deficient samples, 17 of the 40 total samples were <500 mg kg^{-1}, indicating a severe P deficiency at the Borrow Pit. In the Dove Field, only 2 of the 40 total samples were <1000 mg kg^{-1}, indicating adequate P was available for plant uptake. Application rate had a significant affect on plant P concentration, with levels of P much higher in the 143 Mg ha^{-1} treatments than the seeded controls across sites and years (Table 6). In 2004, the 143 Mg ha^{-1} treatment at the Borrow Pit site had significantly higher plant P than all

Table 6. Total plant macronutrient concentrations at increasing Fluff application rates over two growing seasons in the Dove Field and Borrow Pit sites. Values represent means of five composite subsamples replicated four times.

	N		Ca		K		Mg		P		S	
Fluff rate	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004	2003	2004
$Mg\ ha^{-1}$	%		$mg\ kg^{-1}$									
							Dove Field					
0	0.5881 b†	0.4901 a	3511.89 a	3366.95 a	5620.46 a	3567.02 b	2682.85 a	1746.69 a	1729.95 b	991.99 c	521.69 a	250.69 b
17.9	0.5875 b	0.4271 a	3834.19 a	2529.42 a	5692.38 a	3982.50 ab	2555.95 ab	1719.93 a	1999.99 a	1165.73 bc	503.30 a	286.34 b
35.8	0.5770 b	0.4143 a	3498.64 a	2895.25 a	6787.76 a	3945.66 ab	2154.86 bc	1568.66 a	1930.05 ab	1174.90 abc	564.23 a	291.20 b
71.6	0.6314 b	0.4846 a	3528.30 a	3300.29 a	6676.78 a	4523.91 a	2084.98 cd	1634.98 a	2014.04 a	1389.00 ab	546.31 a	358.65 a
143	0.7326 a	0.4787 a	2153.04 a	2420.76 a	6828.59 a	4311.01 a	1678.61 d	1694.7 a	2074.75 a	1446.78 a	452.56 a	357.06 a
							Borrow Pit					
0	0.6301 a	0.4942 a	2607.96 b	3135.49 bc	3027.28 b	2699.42 a	685.63 c	876.34 ab	396.13 b	290.84 d	376.59 a	375.59 a
17.9	0.5205 b	0.2605 b	4621.94 a	2923.89 c	4577.66 ab	1700.20 b	1039.59 bc	582.19 c	717.95 ab	382.04 cd	396.28 a	265.49 c
35.8	0.5025 b	0.3383 b	4325.68 ab	4178.78 ab	4993.39 a	1850.41 b	1090.56 bc	558.40 c	894.40 a	476.23 bc	465.34 a	264.95 c
71.6	0.4758 b	0.3457 b	4543.04 a	4690.59 a	3992.49 ab	1598.29 b	1152.99 b	662.71 bc	747.35 ab	559.93 b	328.25 a	283.76 bc
143	0.5568 ab	0.3270 b	4640.69 a	4413.61 ab	4462.60 ab	1688.18 b	1670.64 a	911.08 a	1005.04 a	777.31 a	456.45 a	341.24 a

† Means in each column for each site with the same letter are not significantly different at the 0.05 probability level.

other treatments (Table 6). The positive relationship seen between application rate and plant P was also noted during a preliminary study of this material on a silt loam soil (unpublished data, 2003). Thus it appears that Fluff application increases plant-available P in soil.

Plant K concentrations were highly variable and ranged from 1057 to 13382 mg kg^{-1}, with higher concentrations in the Dove Field than the Borrow Pit. Plant K concentration decreased significantly over time at both sites. The normal range for K concentrations in plant tissue is 10000 to 40000 mg kg^{-1} but older tissues generally have lower concentrations (Munshower, 1994). Given that samples were harvested late in the season at peak standing biomass, the apparent deficiency may be more a result of older tissue than a deficiency in the soil. In the Dove Field, plant K concentration was unaffected by application rate in 2003, but in 2004 the 143 Mg ha^{-1} treatment had significantly higher plant K than the seeded control. At the Borrow Pit, differences in 2003 were small, but in 2004 the seeded control had significantly higher plant K than all other treatments (Table 6). This inverse relationship may be due to a similar mechanism as that of plant N concentration, as the significantly lower biomass in seeded controls indicated a severe inhibition of plant growth in the control soil.

Plant Ca concentrations ranged from 707 to 6490 mg kg^{-1} and did not change over time at either site. The normal range of Ca concentrations in grasses ranges from 2000 to 5000 mg kg^{-1} (Munshower, 1994). Plant Ca concentration was unaffected by application rate in the Dove Field and was relatively unaffected in the Borrow Pit (Table 6).

Plant Mg concentrations ranged from 231 to 3180 mg kg^{-1} and decreased over time at both sites. All samples at the Dove Field site were within the normal range of grass Mg concentrations of 1000 to 5000 mg kg^{-1} (Munshower, 1994). However, at the Borrow Pit site, 25 of 40 samples were below this range, indicating a Mg deficiency at this site. The Borrow Pit site exhibited a strong application rate effect on plant Mg concentration, with a mean concentration of 1671 mg kg^{-1} in the 143 Mg ha^{-1} treatment compared to 686 mg kg^{-1} in the seeded control in 2003 (Table 6). By 2004, the effect was still evident, but the seeded control had a higher Mg concentration relative to the lower application rates. In 2003, the effect of application rate on plant Mg concentration in the Dove Field was opposite that observed in the Borrow Pit, with a high concentration of 2683 mg kg^{-1} in the seeded control compared to 1679 mg kg^{-1} in the 143 Mg ha^{-1} treatment. No effects of application rate on plant Mg concentration were found in 2004. This inverse relationship between sites and application rates on plant Mg concentration in 2003 could likely be due to the deficient K concentrations in both the Borrow Pit soils (Torbert et al., unpublished data, 2006) and vegetation, as a deficiency in one of these cations can be compensated for by increased uptake of another (Mengel and Kirkby, 1982).

Plant S concentrations ranged from 190 to 684 mg kg^{-1} and decreased over time at both sites. All samples analyzed at both sites fall well under the range of plant S concentrations from 1000 to 10 000 mg kg^{-1} specified in Munshower (1994). Either both sites are deficient in S, as may well be the case, or the species analyzed have a lower S requirement, as S is indicative of protein content, and the three dominant warm-season grasses in the plots are generally low in protein, especially late in the growing season. At both sites, application rate had no effect on plant S concentration in 2003. However, in 2004 plant S concentration increased with increasing Fluff application at the Dove Field site, while the seeded control and 143 Mg ha^{-1} treatments had the highest plant S concentrations at the Borrow Pit site (Table 6).

Micronutrients and Nonessential Elements

Plant Fe concentrations ranged from 46 to 237 mg kg^{-1} at the Dove Field and from 168 to 24 805 mg kg^{-1} at the Borrow Pit. Levels increased over time in the Borrow Pit but remained unchanged in the Dove Field. The normal range of Fe in plant tissues is 18 to 320 mg kg^{-1} with a toxic level $>$1000 mg kg^{-1} (Kabata-Pendias, 2001). All samples from the Dove Field were in the normal range, but in the Borrow Pit, only 3 of 40 total samples analyzed were in this range. Additionally, of the Borrow Pit samples analyzed, only nine samples were less than toxic levels, with all nine taken from treatments with the two highest application rates. Furthermore, eight Borrow Pit plant samples contained Fe concentrations $>$10 000 mg kg^{-1}, most of which were located in seeded control plots. Application rate had no effect on plant Fe concentration at the Dove Field, but increasing application rate led to a substantial reduction in plant Fe in the Borrow Pit, where the mean concentration in the unseeded controls was 10 542 mg kg^{-1} compared to 651 mg kg^{-1} in the 143 Mg ha^{-1} treatment in 2003 (Table 7). The effect of application rate on plant Fe was still evident in 2004, although levels increased to 14 066 mg kg^{-1} in the seeded controls and 1708 mg kg^{-1} in the 143 Mg ha^{-1} treatment. Surprisingly, soil Fe in the top 5 cm of the Borrow Pit soil in 2003 actually increased with increasing application rate (Torbert et al., unpublished data, 2006). This increase in soil Fe and subsequent reduction in plant Fe is most likely the result of the significantly increased pH in the Borrow Pit soil with increasing Fluff application, as this would make Fe unavailable for plant uptake (Torbert et al., unpublished data, 2006). However, because the influence of Fluff on pH most likely diminished deeper in the soil profile, Fe was probably still available for root absorption as an inverse relationship to amount of Fluff applied, as evidenced in the concentrations of plant Fe.

Plant Mn concentrations ranged from 13 to 228 mg kg^{-1} and remained unchanged over time at both sites. All samples from the Dove Field were in the normal range of 30 to 300 mg kg^{-1} for plant Mn concentration, and only three samples from the Borrow Pit were in the deficient range (Kabata-Pendias, 2001). Unexpectedly, the four samples collected from the 143 Mg ha^{-1} treatment in 2004 in the Borrow Pit had the four lowest Mn concentrations of all samples analyzed. Application rate had no effect on plant Mn concentration in the Dove Field

Table 7. Total plant micronutrient and nonessential element concentrations at increasing Fluff application rates over two growing seasons in the Dove Field and Borrow Pit sites. Values represent means of five composite subsamples replicated four times.

	Fe		Mn		Ba		Na	
Fluff rate	2003	2004	2003	2004	2003	2004	2003	2004
$Mg\ ha^{-1}$	$mg\ kg^{-1}$							
	Dove Field							
0	100.05 a†	134.26 a	124.67 a	137.81 a	64.69 a	47.91 a	115.79 c	88.38 c
17.9	90.75 a	74.70 a	105.39 a	97.43 a	57.63 ab	25.28 a	150.10 bc	119.80 b
35.8	85.31 a	66.01 a	120.70 a	113.31 a	49.80 ab	38.48 a	184.08 ab	117.85 b
71.6	74.08 a	122.14 a	105.61 a	118.98 a	41.56 ab	37.39 a	197.01 ab	128.06 b
143	65.86 a	75.96 a	83.30 a	102.34 a	23.88 b	26.44 a	239.84 a	170.03 a
	Borrow Pit							
0	10 542.00 a	14066.00 a	87.54 a	145.73 a	23.00 a	42.45 a	121.09 b	158.23 a
17.9	2 774.85 b	7345.53 ab	102.26 a	64.03 bc	17.65 ab	8.78 b	245.25 a	202.91 a
35.8	1 680.65 bc	9896.28 a	107.63 a	79.06 b	15.85 ab	13.64 ab	187.50 ab	168.24 a
71.6	507.39 c	2342.94 b	73.80 ab	47.53 bc	5.63 b	8.4 b	183.53 ab	147.36 a
143	650.74 bc	1708.20 b	43.15 b	23.51 c	4.85 b	5.075 b	226.89 a	165.31 a

† Means in each column for each site with the same letter are not significantly different at the 0.05 probability level.

but had an inverse affect on plant Mn in the Borrow Pit in 2004, where mean plant Mn concentration fell from 146 mg kg^{-1} in the seeded controls to 24 mg kg^{-1} in the 143 Mg ha^{-1} treatment (Table 7). This difference in application rate on plant Mn concentration between sites was most likely due to the significant changes in pH, as Mn availability increases with decreasing pH (Kabata-Pendias, 2001). At the Borrow Pit, mean pH levels ranged from four to seven from the seeded control to the 143 Mg ha^{-1} treatments, but changes in pH were not observed in the Dove Field, which remained at about 6 (Torbert et al., unpublished data, 2006). This corresponds directly to what was observed in plant concentrations across treatments and sites.

Plant Na concentrations ranged from 79 to 346 mg kg^{-1} and decreased over time at both sites. Because Na may not be required by all plants, and species vary considerable in their tolerance to Na, a normal range is difficult to determine. Regardless, application rate had a direct effect on plant Na concentration at the Dove Field site, as mean Na concentration ranged from 116 mg kg^{-1} in the seeded control to 240 mg kg^{-1} in the 143 Mg ha^{-1} treatment in 2003 (Table 7). This effect was also present in 2004. In the Borrow Pit, rate effects were similar in 2003, with a mean Na concentration of 227 mg kg^{-1} in the 143 Mg ha^{-1} treatment compared to 121 mg kg^{-1} in the seeded controls. However, in 2004, no effect of application rate on plant Na concentration was observed at the Borrow Pit.

Plant Ba concentrations ranged from 2 to 162 mg kg^{-1} with no change over time at the Borrow Pit but a decrease in Ba concentration over time in the Dove Field. Barium is not required for plant growth but is commonly found in plant tissues, with a toxicity level greater than 500 mg kg^{-1} (Kabata-Pendias, 2001). All samples analyzed were well below toxic levels. At both sites in 2003, increasing application rate significantly decreased plant Ba concentration, from 65 mg kg^{-1} in the seeded control to 24 mg kg^{-1} in the 143 Mg ha^{-1} treatment in the Dove Field, and from 23 to 5 mg kg^{-1} in the respective Borrow Pit treatments (Table 7). No effect of application rate on Ba concentration was observed in the Dove Field in 2004 but a similar treatment effect was observed in the Borrow Pit in both years.

CONCLUSIONS

This study evaluated an uncomposted waste product for establishing native grasses on disturbed Army training lands. Planted grasses dominated the sites where they were seeded, with switchgrass comprising the highest percentage of both relative composition and basal cover. Switchgrass responded most positively to Fluff application at both sites, with big bluestem responding well at the more unproductive site. Indiangrass appeared to be unsuited to Fluff-amended soil. Biomass increased dramatically at both sites with increasing Fluff application, as the 143 Mg ha^{-1} treatments had 40 times and 2.5 times more biomass than the seeded controls at the highly disturbed and relatively productive sites, respectively, in 2004. Plant nutrition was also improved at both sites, however, due to very distinctive soils between sites, effects were dissimilar between sites. At the more productive site, plant N, P, K, and Na concentrations increased significantly with increasing Fluff application. At the highly disturbed site, plant P and Na concentrations also increased with increasing Fluff, as well as Mg concentration. An apparent Fe toxicity problem at the highly degraded site was alleviated by high applications of Fluff, while the controls and lower application rates accumulated extremely high levels of plant Fe. Plant Ba concentration was also reduced by increasing application of Fluff at both sites. The improved plant nutrition and significant improvements in cover and biomass of perennial native vegetation at both sites indicates an undecomposed organic material such as Fluff can positively influence the establishment of native vegetation in disturbed soils with highly variable properties. Results indicate that greater benefits are achieved with higher levels of soil degradation when using undecomposed waste to aid in establishment of warm-season prairie grasses.

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